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On the feasibility of solar-powered irrigation

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ABSTRACT

Solar-powered agricultural irrigation is an attractive application of renewable energy. However, to be practical it must be both technically and economically feasible. Here, a method is presented for calculating the feasibility of photovoltaic-powered (PVP) irrigation. The feasibility is expressed as a function of location, which includes climate data, aquifer depth and cost, including local political policies such as carbon taxes. A discounted cash flow analysis is used to compare the lifecycle costs of photovoltaic-, diesel engine- and electrical grid-powered irrigation systems. Five examples illustrate the method's application. These results suggest that PVP irrigation is technically and economically feasible, provided that there is enough land available for the solar array.

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Nomenclature

A	annual cost ($)
A_{CO_2}	annual carbon tax ($/year)
A_f	field area (m^2)
$A_{O\&M,\ cleaning}$	annual operating and maintenance costs of solar panel cleaning ($/year)
$A_{O\&M,d}$	annual operating and maintenance costs of diesel system ($/year)
A_r	ratio of solar panel array area to field area
A_s	area of the solar array (m^2)
C_{CO_2}	net present value of lifecycle carbon taxes ($)
C_{cool}	capacity of the diesel generator engine coolant tank (L)
C_{diesel}	total diesel system capital cost ($)
$C_{diesel\ fuel}$	net present value of lifetime diesel fuel costs ($)
C_E	cost of an arbitrary maintenance event ($/event)
C_{elec}	capital cost of grid-based system ($)
C_{fuel}	net present value of the fuel costs ($)
$C_{fuel\ elec}$	net present value of the lifetime electricity cost ($)
C_{gen}	retail generator price ($)
C_{inc}	net present value of renewable energy incentives and income tax rebates ($)
C_{LCC}	net present value of total system lifecycle cost ($)
C_M	annual cost of an arbitrary maintenance event ($/year)
$C_{M,air}$	annual cost of diesel engine air filter changes ($/year)
$C_{M,oil}$	annual cost of diesel engine oil change ($/year)
$C_{M,oil,filt}$	annual cost of diesel engine oil filter changes ($/year)
$C_{O\&M}$	net present value of operation and maintenance costs ($)
$C_{O\&M,pv}$	total lifecycle operating and maintenance cost of photovoltaic system ($)
C_{oil}	capacity of the diesel generator lubrication oil tank (L)
C_{PV}	capital cost of the photovoltaic array
C_{tr}	retail transformer price ($)
C_{sys}	system capital cost ($)
D	number of days to clean photovoltaic panels
ET	evapotranspiration rate (m/day)
F	load factor
F_E	replacement frequency
F_M	annual frequency of maintenance event
FV	future value ($)
G	fixed annual electricity price increase ($/kWh/year)
G_d	number of days in the growing season (days)
g	gravitational constant (9.81 m/s^2)
H_d	annual number of hours the diesel generator operates (h/year)
H_p	number of equivalent peak sunshine hours (h/day)
h	pumping head (m)
I_{av}	average solar insolation (kWh/m^2/day)
I_{max}	solar radiation used by solar panel manufacturer for power rating (W/m^2)
I_p	peak solar radiation (w/m^2)
I_{tr}	transformer installation cost ($)
i	discount rate (%)
L	labor price ($/h)
M_C	molar mass of carbon (kg/mol)
M_{CO_2}	molar mass of CO_2 (kg/mol)
m_{CO_2}	mass of CO^2 produced in 1 year (kg/year)
n	system lifetime (years)
$P_{cleaning}$	net present value of solar panel cleaning cost ($)
$P_{gen,\ rated}$	power rating for diesel generator (kW)
P_{inv}	net present value of inverter replacement costs ($)
P_p	pump power (W)
PV	present value ($)
Q	volumetric flow rate (m^3/s)
R_{CO_2}	carbon tax rate ($/kg CO_2)
R_{tr}	transformer power rating (kVA)
t	time (h)
U_{init}	starting unit price of electricity ($/kWh)
U_{iniv}	unit cost of electronics ($/W)
$U_{NPV,\ diesel}$	net present value of the unit cost of diesel fuel ($/L)
$U_{NPV,\ elec}$	net present value of the unit cost of electricity ($/kWh)
U_{pv}	unit cost of photovoltaic array ($/W)
V_{hour}	hourly fuel consumption (L/h)
W_p	power rating of the photovoltaic array
W_{tr}	transformer weight (lbs)
w_{carbon}	mass fraction of carbon in the diesel fuel
x	number of years after which an arbitrary expenditure occurs (years)
y	project year in which electronics are replaced
η_p	pump efficiency
η_{sa}	solar array conversion efficiency
ρ	water density (kg/m^3)
ρ_{fuel}	density of the diesel fuel (kg/L)

1. Introduction

1.1. Motivation

Fossil fuel power is a major contribution to carbon-based climate change and air pollution. In addition, rising fossil fuel costs and energy self-sufficiency have made the development of viable sources of clean energy critical for many parts of the world. Photovoltaic-powered (PVP) pumping for crop irrigation has been suggested as an application, as it is an energy intensive activity that

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is well suited for implementation with renewable energy sources [1]. However, to be practical, PVP irrigation, like all alternative energy applications, must be both technically and economically feasible. For irrigation, this feasibility is dependent on many factors, such as crop type, location, water depth, conventional energy costs, government incentives and carbon taxes. In this paper this feasibility is addressed.

1.2. Background and literature

PVP irrigation for very small farms has been well-studied and implemented [1,2]. In early 2003, Shell and WorldWater & Power Corporation installed a demonstration 36-kW, 50 HP PVP pump powered by a 108-foot long solar array in the San Joaquin Valley, California [3]. This was a demonstration unit; PVP irrigation for larger commercial farms has not been implemented.

Previous feasibility studies evaluated either the economic feasibility or the technical feasibility of PVP irrigation. Most of the studies are system size-specific and location-specific. Studies focusing on systems with power requirements on the order of 1 kW have been conducted for sites in Namibia, Jordan and India [4–6]. Site-specific technical feasibility assessments based primarily on solar insolation have been conducted in Saharan Africa, Botswana and Sudan [7–9]. A method for sizing a PVP irrigation system based on climate, geographic location, soil quality and crop water requirements was applied to 10-hectare olive grove near Badajoz, Spain [10]; economic costs were not considered.

The Jordanian study [5] addresses both technical and economical feasibility of PVP pumping for drinking water, using the cost annuity method. Its results concur with the other studies cited: for the geographic locations selected, PVP pumping for drinking water or for irrigation is economically feasible at low power requirements, such as when pumping at high flow rates from shallow wells and at low flow rates from deeper wells.

The literature concludes that PVP irrigation is both technically and economically feasible for very small systems on the order of one acre. However, a generalized method for determining both technical and economic feasibility, applicable to systems of any size, has not yet been developed.

1.3. Approach

Here, a generalized method to determine the technical and economic feasibility of PVP irrigation systems is developed. Technical feasibility is determined as a function of crop type and geographic location, which includes the factors of climate, land quality, groundwater depth and water recharge rate. The maximum required daily volumetric flow rate for crop irrigation is determined from the crop's maximum evapotranspiration rate during its growing season. The maximum evapotranspiration rate is a function of crop type, soil conditions and weather conditions. The maximum daily required flow rate is used to determine the pumping power needed. The corresponding solar panel area needed to provide the required power is calculated using average monthly solar insolation and compared to the total field area.

If technical feasibility is defined as the ability to put together a system with existing technologies and have it perform in the desired fashion, then solar-powered irrigation is technically feasible for all locations where agricultural irrigation is needed. Following the sizing method presented here, one will be able to determine how much land is required for the solar array. Assuming one has the land available, including roofs of farm buildings, there is no other technological breakthrough needed.

One can argue that there are no deep-well solar-powered pumps on the market, which is true. However, there are plenty of deep-well commercial pumps available that use conventional power sources. Making them operate using solar power is a matter of assembling the proper electronics. So, technical feasibility is still determined by whether or not one has the land available.

Economic feasibility is a function of crop type and geographic location. Here, methods of discounted cash flow (DCF) analysis [11] are applied. The net present value of the lifetime system costs of a PVP irrigation system are compared to that of diesel-powered and electrical grid-powered irrigation systems. After determining the power required and the needed solar panel area, the diesel and electrical components are selected with the same power requirements. Capital costs, annual operating and maintenance costs, and fuel costs for all three systems are determined. The PVP irrigation system is considered economically feasible if its lifetime system cost is the lowest among all alternatives.

1.4. Results and conclusions

The results for technical feasibility agree with those from past studies, showing that PVP irrigation is technically feasible in areas with high solar insolation. As defined in this paper, there are no technological barriers to implementing PVP irrigation, provided one has enough land available for the PV array.

PVP irrigation is economically feasible for all examples considered. Although the capital costs of the photovoltaic panels exceed those of both the diesel generator and the electrical transformer, the dominant costs from a lifecycle perspective are the costs of a 25-year supply of diesel fuel or electricity.

2. Analysis

2.1. Assumptions

In this analysis, a new pumping system that uses conventional diesel power, electrical power from the grid, or alternatively, solar power from photovoltaic arrays to power the irrigation pumping is to be installed. The photovoltaic systems are assumed to be mounted horizontally and do not incorporate any sun tracking. Locations are assumed to be above local aquifers, so there is no need to transport water over large distances. The water in the aquifer is of suitable quality and there is no need to desalinate or treat the water. In addition, it is assumed the location has sufficient rainfall so that the water extracted from the aquifer during periods of irrigation will be replaced over the course of the year. For a given location an appropriate crop type is selected. Also, it is assumed that the land has enough topsoil and/or fertilizer to produce healthy plants, so soil quality is not considered.

2.2. Exemplar irrigation system

Fig. 1 is a schematic of a representative simple PVP irrigation system. It consists of a photovoltaic solar array, control electronics,

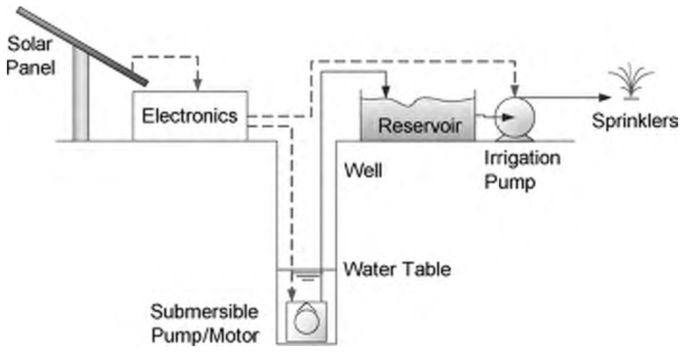

Fig. 1. Schematic of a PVP irrigation system.

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a submersible pump powered by a DC motor or an AC motor, and an inverter. Although only one well and pump are shown in the figure, often more than one well and pump are needed to irrigate larger fields [12]. Not shown in the figure are the water distribution components at the field level, such as the irrigation ditches and piping networks. These components are not included in the analysis, as they are also required by the conventional energy-powered systems used for comparison. Although a reservoir, irrigation pump and sprinklers are shown, they may not be necessary for some irrigation. For this analysis, it is assumed that the reservoir is covered, so evaporation from the reservoir is ignored.

The major difference between photovoltaic-, diesel- and grid-powered irrigation systems is the power source. The schematics for the diesel- and grid-powered systems are almost identical to Fig. 1. A diesel engine/generator set or an electrical transformer and transmission lines are substituted for the photovoltaic array.

2.3. Irrigation requirements

In some areas, irrigation may only be necessary during dry periods within the growing season. In other areas, year-round irrigation may be required. The requirements for the type of irrigation are local sunlight, groundwater, rain, soil conditions and crop type.

2.3.1. Determining solar insolation

Solar insolation is the sum of the solar radiation received over the course of a day at the earth's surface, and is measured in kWh/m^2/day. On a cloudy day, the light is scattered more than it is on a clear day, hence the amount of light reaching the surface is diminished. Regions of similar latitude having many cloudy days, such as the Amazon rainforest, will have much lower average insolation levels than, say, the Sahara desert. This is illustrated in Fig. 2, which shows the yearly average insolation over the earth's surface.

The areas with highest annual average solar insolation are regions near the equator with small variations in insolation between summer and winter, including Saharan Africa, India, Central Australia, and Central America. Geographic regions off the equator typically experience their peak levels of daily solar insolation during their summer months. Crops are typically planted and grown during the spring and summer, so the average monthly solar insolation during this time is of key importance. The insolation during the growing season is a critical factor used in this analysis for the feasibility of solar-powered irrigation.

The three-boxed geographic regions in Fig. 2 are the Southwestern United States, Spain and the Mediterranean, and the Middle East. All three are off the equator, have high average insolation and require irrigation during the summer, as is demonstrated in Section 2.2. The five representative cases presented later are from these three regions.

2.3.2. Water

Irrigation requires readily accessible groundwater. For sustainable farming, the amount of water removed from the groundwater source during periods of irrigation must be replenished during the winter months. Figs. 3–5 show the hydrological structure and groundwater recharge rates for the Southwestern United States, Spain and the Middle East, respectively. All three regions have high solar insolation and require irrigation during their summer months. The regions also have low to medium recharge rates; hence irrigation needs to be carefully planned. Such issues are beyond the scope of this paper, since they do not affect the technical or financial feasibility of PV-powered irrigation systems. However, as surface and shallow water supplies become scarce, the tendency to tap deeper resources will increase.

2.4. Technical feasibility

A PVP irrigation system is considered to be technically feasible if there is enough land available to mount the solar array. Here it is assumed that the land required for the solar panels is approximately the same as the area of the solar panels.

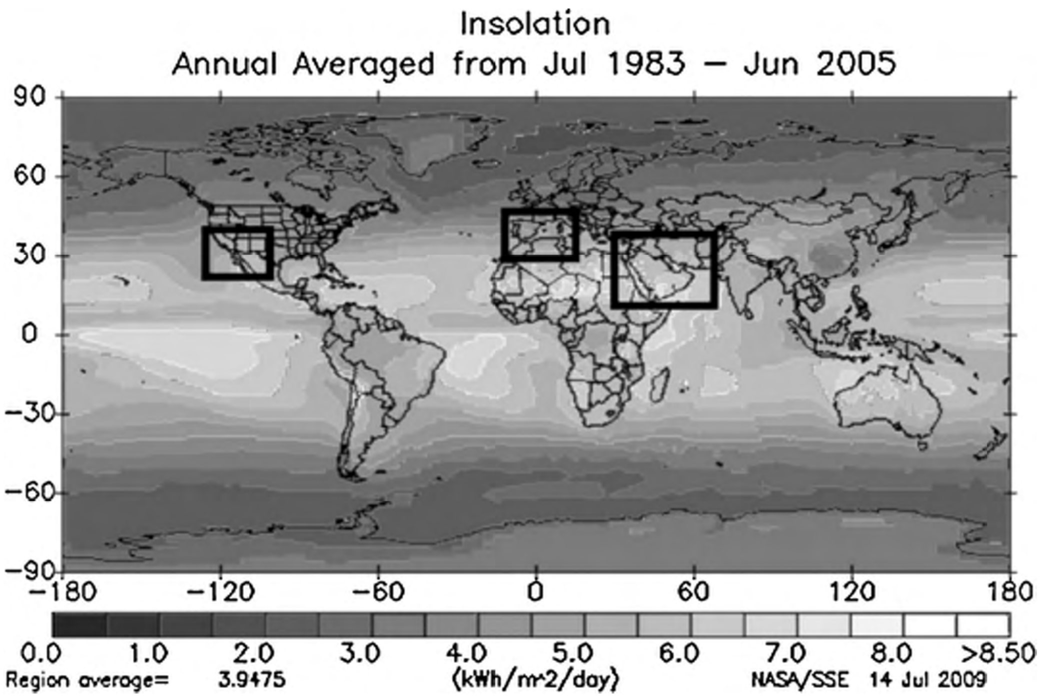

Fig. 2. Global average solar insolation. Selected regions with high insolation, left to right, are the Southwestern United States, Spain and the Mediterranean region, and the Middle East. Image courtesy of NASA Langley Research Center Atmospheric Science Data Center from the Surface meteorology and Solar Energy Dataset (http://eosweb.larc.nasa.gov) [45].

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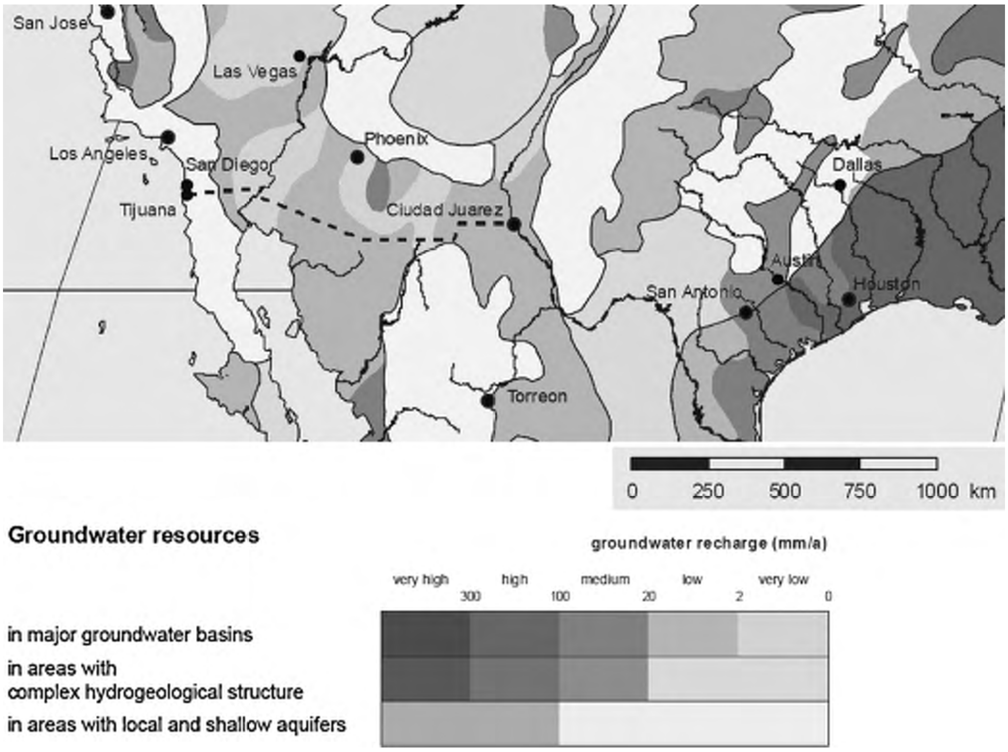

Fig. 3. Groundwater resources and recharge rates for the Southwestern United States [46].

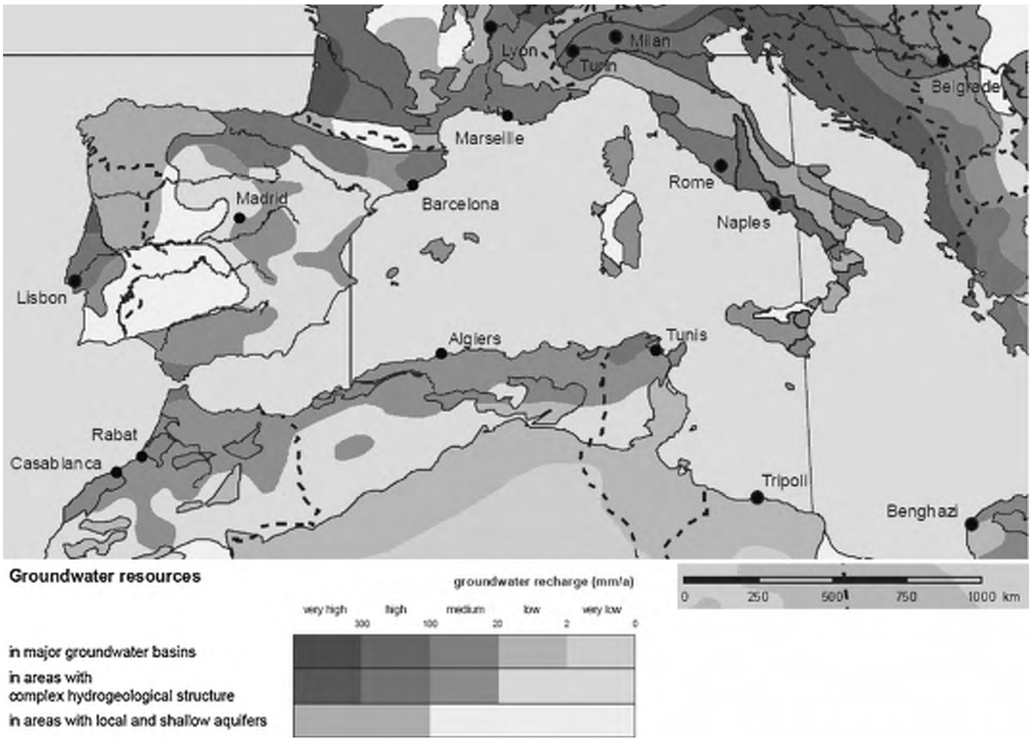

Fig. 4. Groundwater resources and recharge rates for the Mediterranean region [47].

The required solar panel array area, A_s is

$$A_s = \frac{P_p}{I_p \eta_{sa}} \tag{1}$$

where P_p is the power required for water pumping in Watts, I_p is the average amount of solar radiation incident on a panel during the peak sunshine hours and η_{sa} is the efficiency of the solar array and its electronics.

The power required for water pumping is given by

$$P_p = \frac{\rho g h Q}{\eta_p} \tag{2}$$

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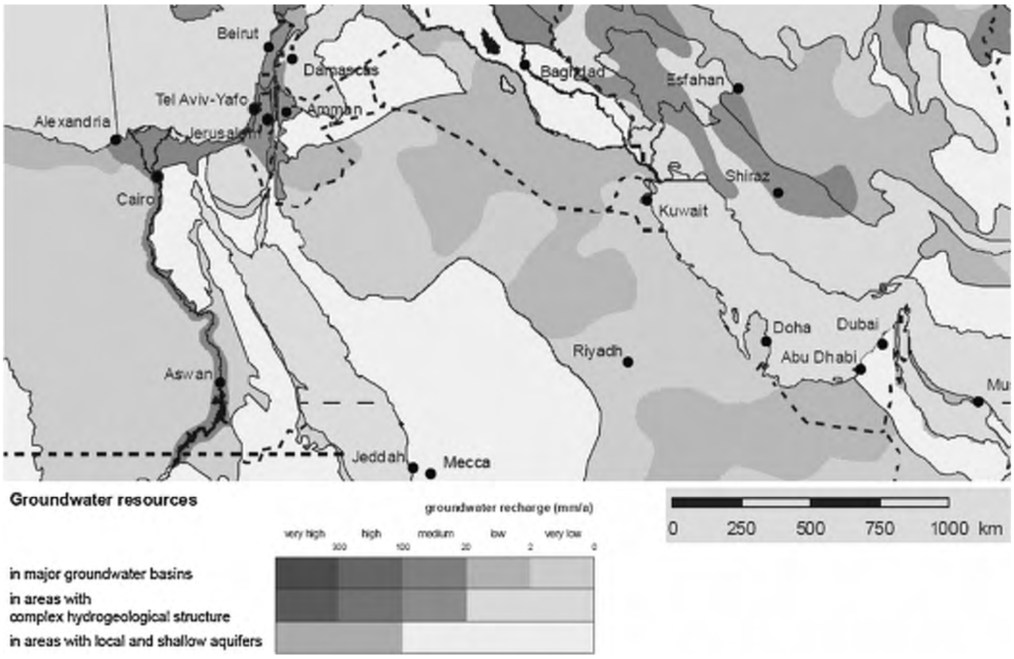


Fig. 5. Groundwater resources and recharge rates for the Middle East [47].

where Q is the maximum volumetric flow rate in m^3/s, ρ is the density of water, g is the gravitational constant, h is the total dynamic head in meters, and η_p is the pump/motor efficiency.

The total dynamic head consists of the height the water must be lifted, plus the energy losses in meters due to pipe friction. For deep-well pumping (i.e. greater than about 10 m), the total dynamic head, h, is approximated by the local aquifer depth. For surface pumping, dynamic head is calculated from pipe friction losses.

The maximum flow rate required is given by

$$Q = \frac{ET \times A_f}{3600t} \tag{3}$$

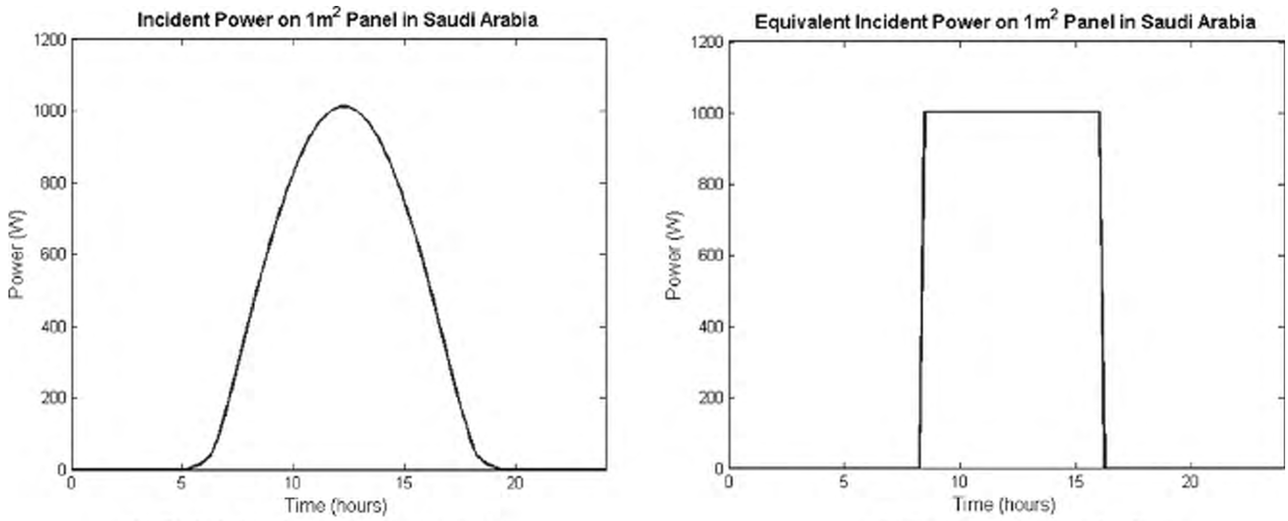
where ET is the maximum evapotranspiration rate for the given crop in m/day, A_f is the field area in m^2, and t is the number of pumping hours per day.

For the photovoltaic system, t is equivalent to the number of peak sunshine hours per day, H_p. At the earth's surface, the standard peak solar radiation received is approximately 1000 W/m^2 (1 kW/m^2) [13]. Solar radiation for an arbitrary location over the course of a clear day has a distribution as shown in Fig. 6(a), below. One can see that the level of radiation varies. The total area under the curve is the amount of total solar insolation received in 1 day. The number of peak sunshine hours is given by the equivalent time at peak solar radiation that produces the same insolation, as shown in Fig. 6(b). The areas under the curves in Fig. 6 are equal.

The average monthly solar insolation, I_{av}, for a geographic area is found using:

$$I_{av} = H_p \times I_p \tag{4}$$

where I_p is 1 kW/m^2 and H_p is the average number of peak sunshine hours per day during the month requiring the largest volume of water for irrigation. This is the amount of time the pump is assumed to run, so H_p is equal to t.



(a) Typical clear sky irradiance over one day

(b) Equivalent maximum irradiance

Fig. 6. (a) Typical clear sky irradiation over the course of 1 day and (b) maximum irradiation over an equivalent number of hours.

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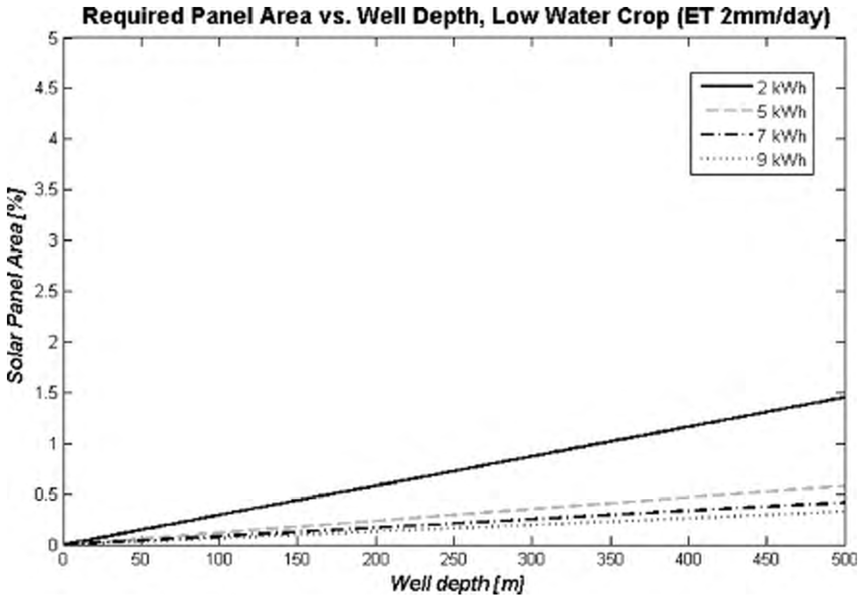

Fig. 7. Percent panel area as a function of well depth for a crop with low water requirements (2 mm/day), such as olives grown in Badajoz, Spain, during the month of June.

Substituting Eqs. (2)–(4) into (1) yields an expression for solar panel array area as a function of location (solar insolation, field area and well depth) and crop type (evapotranspiration rate, *ET*):

$$A_s = \frac{\rho g h \times ET \times A_f}{3600(1000\,\mathrm{W/kW}) I_{av} \eta_{sa} \eta_p} \tag{5}$$

Eq. (5) can be rearranged to give the area ratio as a function of location and crop type:

$$A_r = \frac{A_s}{A_f} = \frac{\rho g h \times ET}{3600(1000\ \mathrm{W/kW}) I_{av} \eta_{sa} \eta_p} \tag{6}$$

where A_r is the ratio of solar panel array area to field area.

2.5. General trends

Figs. 7–9 show the ratio of solar panel area to field area as a function of well depth at various levels of solar insolation for crops having low (2 mm/day, such as olives grown in Badajoz, Spain, during the month of June), medium (5 mm/day, such as corn in Riyadh, Saudi Arabia,) and high (8 mm/day, such as tomatoes in Wadi-Wala, Jordan,) evapotranspiration rates, respectively [10,14]. As expected, more solar array area is needed for PV-powered irrigation as the daily crop water requirements and well depth increase. However, at reasonably high levels of daily insolation, such as at 5 kWh/m^2-day, the amount of solar array area required for irrigating crops with high-water requirements (Fig. 9) is less than 2.5% of the total field area, even when pumping from very deep wells (500 m). This means that if there is no additional land available to hold the solar array, the crop field will be reduced by less than 2.5%. The geographic regions cited earlier have an average daily solar insolation of 7 kWh/m^2-day during the summer. Based on these figures, the required solar array area in these regions is expected to be less than 1.5% of the total field area, even when irrigating from deep wells that require high pumping power; this is not a huge reduction of crop land.

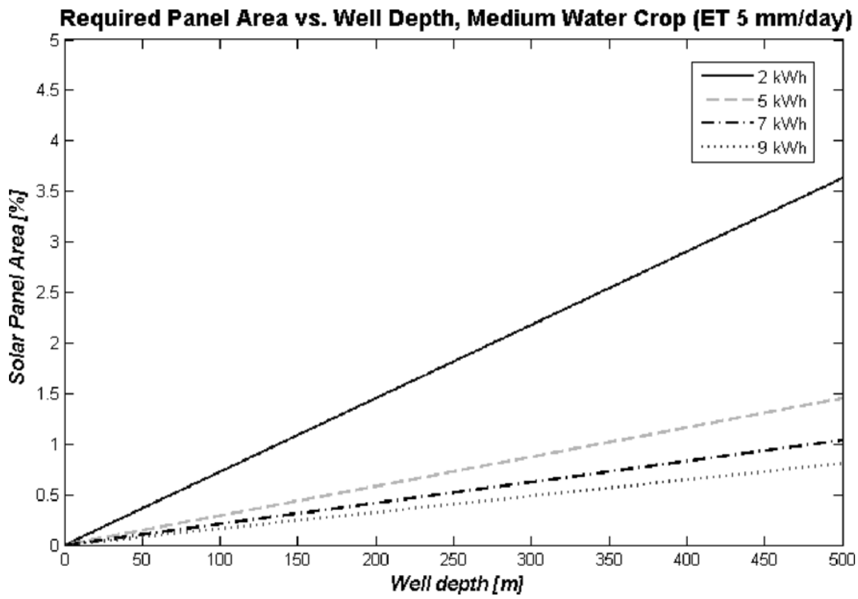

Fig. 8. Percent panel area as a function of well depth for a crop with medium water requirements (5 mm/day) such as corn grown in Riyadh, Saudi Arabia.

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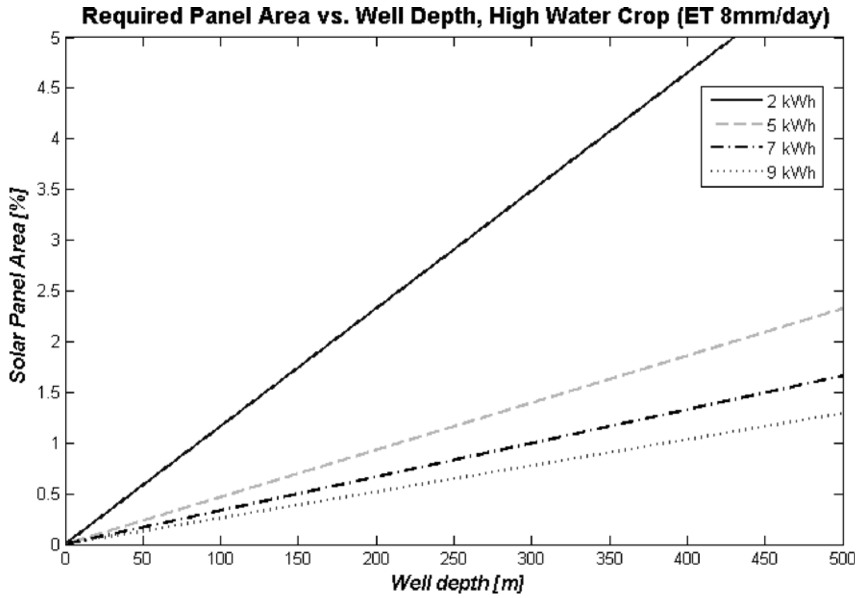

Fig. 9. Percent panel area as a function of well depth for a crop with high-water requirements (8 mm/day), such as tomatoes grown during the summer in Wadi-Wala, Jordan.

In regions receiving low amounts of solar insolation, solar array area increases drastically with well depth and daily crop water requirements. However, regions with very low average daily solar insolation (2 kWh per day) are close to the poles and are not usually farmed and/or irrigated, so the fact that a high-water crop (Fig. 9) requires a solar array taking up over 5% of the field area when irrigating from a deep well is somewhat meaningless. So, in areas requiring irrigation with reasonable amounts of average summer insolation (4–5 kWh/m^2-day), solar-powered irrigation is technically feasible, and, if one has no additional land for panels, the total solar array area will reduce the field area by less than 1.5%.

2.6. Economic feasibility

2.6.1. Assumptions

Here it is assumed that PVP irrigation is economically feasible if its lifecycle costs are lower than those of comparative conventionally powered diesel and electric grid-based systems. Although wind turbines can also be used to power irrigation systems, its study was beyond the scope of this work.

Lifecycle costs include the equipment capital costs, maintenance costs, operational costs, fuel costs and equipment salvage value. In our approach, a comparative discounted cash flow (DCF) method is used [11]. With DCF, all future costs, such maintenance costs after 2 years, are converted to equivalent current amounts (present values) via a discount rate, an assumed constant interest rate. This discount rate assumes that the difference between inflation and the rate at which a bank charges interest is constant. Future costs are adjusted to their present values using the following equation:

$$PV = \frac{FV}{(1+i)^x} \tag{7}$$

where PV is the present value, FV is the future value, i is the discount rate and x is the number of years in the future when the future expenditure occurs.

Here only differences between alternative power systems will be compared, so when the cost differences of the solar-powered, diesel-powered and electric grid-powered irrigation alternatives are compared, costs associated with components present in all of these irrigation schemes are not included. It is assumed that a submersible pump/motor will be used, and that the same pump can be powered by electricity produced through solar panels, diesel generators and from electricity from the grid. So, the submersible pump/motor cost is not included in the analysis. Similarly, the costs of the reservoir, water distribution system and well drilling are also not included in the analysis, as they are assumed to be independent of the power source used.

2.6.2. Capital costs

2.6.2.1. Photovoltaic system. The capital cost of the photovoltaic array, with its wiring, support structures, installation, inverter and related electronics, is given by

$$C_{pv} = W_p U_{pv} \tag{8}$$

where C_{pv} is the capital cost of the solar array, W_p is the power rating of the array in Watts and U_{pv} is the unit cost in USD per Watt.

The peak power rating of the array is found using:

$$W_p = A_s I_{\max} \eta_{sa} \tag{9}$$

where A_s is the area of the solar array calculated for the location, using Eqs. (5) or (6), η_{sa} is the efficiency of the solar array and $I_{\max}$ is the solar radiation used by the manufacturer for its power rating (typically 1000 W/m^2).

2.6.2.2. Diesel system. The power rating for the appropriate diesel generator to drive the pump, $P_{gen,rated}$, is

$$P_{gen,rated} = \frac{P_p}{F} \tag{10}$$

where P_p is the power required by the pump/motor from Eq. (2) and F is the load factor.

The capital cost of the generator is then estimated using:

$$C_{gen} = \$234.23 P_{gen,rated} + \$3400 \tag{11}$$

Eq. (11) is based on generator dealer pricing [15,16]. Prices are assumed to include the cost of the associated control electronics. An installation cost of 10% of the retail price is assumed [17]. The total capital cost of the diesel generator system, C_{diesel}, is then given by

$$C_{diesel} = (1.1) C_{gen} \tag{12}$$

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Table 1
Calculations of maintenance costs for diesel systems.

Diesel system component	Price per unit (USD)	Replacement frequency (h)	Duration (h)	Labor cost (USD)	Total cost per event (USD)
Air filter	80/filter	600[a]	2[a]	61.12	114.12
Oil/fuel/water separator filter	50/filter	300[b]	2[a]	61.12	111.12
Lubrication oil change	8.32/L	250[b]	0.67[a]	20.37	C_{oil}(8.32) + 20.37
Engine coolant change	1.65/L	12,000 h or 6 years[b]	0.67[a]	20.37	C_{cool}(1.65) + 20.37

[a] From [20].
[b] From [22].

2.6.2.3. Grid-based electrical system. The major capital equipment needed for a grid-based power system is a transformer to step down the grid voltage to a level appropriate for the pumping system. It is assumed that the kilovolt-Amp (kVA) rating of the transformer, R_{tr}, is equivalent to the amount of power in kW the transformer must handle, and that the motor starting power is less than or equal to the maximum required power, P_p, given by Eq. (2):

$$R_{tr} = P_p \tag{13}$$

The installation cost, I_{tr}, is given by [18]:

$$I_{tr} = 42.06(W_{tr}^{0.46}) \tag{14}$$

where W_{tr} is the weight of the transformer.

The total capital cost for the grid-powered system is

$$C_{elec} = C_{tr} + I_{tr} \tag{15}$$

where C_{tr} is the retail transformer price, based on required power [19].

2.6.3. Operating and maintenance costs

Annual operating and maintenance costs and their net present values for each type of system are calculated. A uniform annual series can be converted to lifetime net present value, *PV*, using the following relationship [11]:

$$PV = A\frac{(1+i)^n - 1}{i(1+i)^n} \tag{16}$$

where *A* is the annual cost, *i* is the annual discount rate and *n* is the system lifetime in years.

Scheduled major component replacement costs are also converted to net present value.

2.6.3.1. Photovoltaic system. Operating and maintenance costs of the PV power system, $C_{O\&M,pv}$, consist of the costs associated with cleaning the solar panels and replacing the inverters. Therefore:

$$C_{O\&M,pv} = P_{cleaning} + P_{inv} \tag{17}$$

where $P_{cleaning}$ is the net present value of the cleaning costs and P_{inv} is the net present value of inverter replacement.

It is assumed that all the panels are manually cleaned once a month using a high-pressure water spray. Assuming that a laborer can clean 100 m^2 of panel per hour and that 1 h per day for setup and cleanup is needed, the annual cost in USD for cleaning, $A_{O\&M,cleaning}$, is given by

$$A_{O\&M,cleaning} = 12 \times L\left(\frac{A_s}{100} + 2D\right) \tag{18}$$

where *L* is the local labor cost in USD, including overhead, A_s is the area of the solar array from Eq. (5), and *D* is the number of days it takes to clean the panels in 1 month.

Eq. (16) is then used to obtain the net present value of the maintenance costs.

The electronics are assumed to need replacement once during the solar irrigation system lifetime. Assuming that a one-time payment will be made in the *y*th year of the project, the net present value of the electronics replacement costs is given by

$$P_{inv} = U_{inv}W_p(1+i)^{-y} \tag{19}$$

where P_{inv} is the net present value of the electronics cost, U_{inv} is the unit cost of the electronics, in USD/W, *i* is the annual discount rate, *y* is the number of years between the present time and the date at which the electronics are replaced and W_p is the rated power of the solar array calculated in Eq. (9).

2.6.3.2. Diesel system. The diesel system contains air, fuel, oil, and water separator filters that require replacement. Lubrication oil and coolant need to be replaced periodically. Table 1 shows the costs for filter, oil, and engine coolant changes, where C_{oil} is the capacity of the lubrication oil tank and C_{cool} is the capacity of the engine coolant tank, from [20]. The costs of filters, lubrication oil, and coolant, and the maintenance frequencies, labor and durations are estimated from the literature [20–24]. Here, the labor cost is based on the average cost of labor for a skilled maintenance worker in the U.S. [22]. In general, labor costs for maintenance vary widely by country.

The diesel system is only operated part of the year, during the growing season. The number of hours the diesel system operates annually, H_d, is given by

$$H_d = G_d H_p \tag{20}$$

where G_d is the number of days in the growing season, and H_p is the hours per day the pump operates. The annual frequency of a maintenance event, F_M, is given by

$$F_M = \frac{H_d}{F_E} \tag{21}$$

where H_d is the annual operational hours from Eq. (20) and F_E is the replacement frequency from Table 1 for that particular event.

The annual cost of a specific type of maintenance event, C_M, is then given by

$$C_M = C_E F_M \tag{22}$$

where C_E is the cost of the event from Table 1. The total annual maintenance cost for the diesel system is the sum of the costs of all maintenance events:

$$A_{O\&M,d} = C_{M,cool} + C_{M,air} + C_{M,oil\ filt} + C_{M,oil} \tag{23}$$

This is converted to net present worth using Eq. (16).

2.6.3.3. Grid-based electrical system. The operating and maintenance costs associated with a grid-based electrical system are assumed to be negligible and they are not included here.

2.6.4. Fuel costs

There are no fuel costs associated with the PV panels; fuel costs associated with diesel and grid-based systems to dominate the system lifecycle costs, as shown in the case studies. Calculations for example cases show that deep-well pumping is not economically feasible, regardless of the type of power system used.

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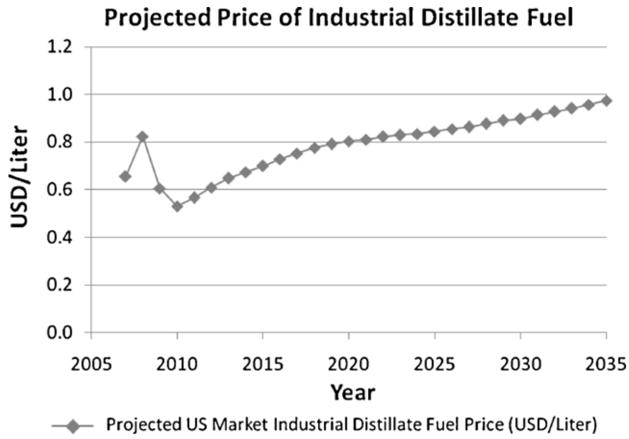

Fig. 10. Projected annual market price of industrial distillate fuel [25].

2.6.4.1. Diesel fuel. The price of diesel fuel varies geographically based on subsidies and taxes. Here its open market price is used. The short term open market price fluctuates based on supply and demand as well as futures trading and speculation, so historical data cannot be used to predict future fossil fuel prices. The US Energy Information Administration publishes an Annual Energy Outlook that includes projections of future fossil fuel prices through 2035, including industrial distillate fuel. Here, the 2010 Annual Energy Outlook projections are used. Fig. 10 [25] shows the projected open market price of distillate fuel oil (diesel fuel) in 2008 USD/L.

The lifetime diesel fuel cost, $C_{diesel\ fuel}$, for a system is calculated using:

$$C_{diesel\ fuel} = U_{NPV,diesel} \times V_{hour} \times H_d \tag{24}$$

where $U_{NPV,diesel}$ is the net present value of the price of diesel fuel per liter, found using Eq. (7), V_{hour} is the amount of fuel the diesel engine consumes per hour and H_d is the annual operating hours, given by Eq. (20).

2.6.4.2. Grid-based electricity. The price and projected increases of electricity vary by geographic region, hence local electricity prices need to be used in this analysis. Electric power plants can be coal-fired, oil-fired, nuclear-powered, geothermal, hydroelectric, etc. Historic price data for each region is needed to determine the local price escalation. For the analysis proposed here, price is assumed to be a gradient (linear) series. The net present value of the unit price of electricity (USD/kilowatt hour is used here) over the system lifetime, $U_{NPV,elec}$, is

$$U_{NPV,elec} = U_{init}\frac{(1+i)^n - 1}{i(1+i)^n} + G\left[\frac{1-(1+ni)(1+i)^{-n}}{i^2}\right] \tag{25}$$

where U_{init} is the initial price of the electricity, G is the fixed amount the price increases each year, i is the discount rate and n is the system lifetime in years [11].

The lifetime electricity cost is calculated using:

$$C_{fuel,elec} = U_{NPV,elec} \times H_d \tag{26}$$

where H_d is the number of hours the electric system runs per year, given by Eq. (20).

2.6.5. Carbon tax and government subsidies

In an effort to reduce global warming, many countries have imposed taxes on the production of CO_2; this increases the annual cost of running a diesel system. The annual carbon tax, A_{CO_2}, is given by

$$A_{CO_2} = R_{CO_2} \times m_{CO_2} \tag{27}$$

where R_{CO_2} is the carbon tax rate and m_{CO_2} is the mass in kg of CO_2 produced per year.

The annual mass of CO_2 produced is found using:

$$m_{CO_2} = \rho_{fuel} V_{hour} H_d w_{carbon}\frac{M_{CO_2}}{M_C} \tag{28}$$

where ρ_{fuel} is the density of the fuel in kg/L, V_{hour} is the amount of fuel the engine consumes per hour, H_d is the annual operating hours given by Eq. (20), w_{carbon} is the mass fraction of carbon in the diesel fuel, M_{CO_2} is the molar mass of CO_2 and M_C is the molar mass of carbon.

Eq. (16) is used to convert the annual cost of the carbon tax to its net present worth. Carbon taxes are not included in the representative case studies presented in Section 3.

Subsidies and incentives for PV systems, such as tax rebates, grants, feed-in tariffs, net metering and renewable energy certificates (RECs), are location-specific and are often complicated. For example, in Germany producers of PV power are paid for the electric power produced and fed into the electric grid based on the type of PV system (i.e. ground mounted, roof mounted) and system size. In California, a combination of investment subsidies, feed-in tariffs and net metering are used; PV plant owners are also able to generate and sell RECs. Feed-in tariffs and net metering require the PV array to be connected to the electrical grid. Subsidies and incentives can make a substantial difference in the economic feasibility of a PVP irrigation system and should be considered when analyzing a system. However, since subsidies and incentives are complex and widely variant, they are not considered here.

Income taxes and credits are also widely variant and complex. We expect that inclusion of income tax credits for large capital expenditures will favor renewable energy systems, since capital costs for renewable energy systems are typically much higher than capital costs for diesel or grid systems. Therefore, income taxes and credits are not considered.

2.6.6. Total lifetime costs

The total system lifetime costs, C_{LCC}, are the sum of the capital costs, C_{sys}, operating and maintenance costs, $C_{O\&M}$, fuel costs, C_{fuel} and carbon tax, C_{CO_2}, minus any alternative energy incentives, C_{inc}:

$$C_{LCC} = C_{sys} + C_{O\&M} + C_{fuel} + C_{CO_2} - C_{inc} \tag{29}$$

2.7. Summary

For a given crop type, well depth and expected amount of solar insolation, the amount of solar array area needed to power an irrigation system is determined by Eq. (5):

$$A_s = \frac{\rho g h \times ET \times A_f}{3600(1000\,\mathrm{W/kW}) I_p \eta_{sa} \eta_p} \tag{5}$$

The lifetime costs of the solar array and comparable diesel and grid-based electric systems are determined using Eq. (29):

$$C_{LCC} = C_{sys} + C_{O\&M} + C_{fuel} + C_{CO_2} - C_{inc} \tag{29}$$

where C_{sys} is determined using Eq. (8) for the solar array, Eq. (12) for the diesel system and Eq. (15) for the grid-based system. The operating and maintenance costs $C_{O\&M}$ are determined using Eqs. (17) and (23) for the solar and diesel systems, respectively. Operating and maintenance costs associated with the grid-based electrical systems are negligible. The fuel costs for the diesel and electric systems are determine either from price projections converted to net present value using Eqs. (8) and (24), or by approximating costs as gradient series using Eq. (25) and then calculating the lifetime cost using Eq. (26).

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Table 2
Technical feasibility parameters for representative cases by location.

Location	Badajoz	Riyadh	Albuquerque	Tell-Amara	Wadi-Wala
Crop type	Olive trees[a]	Maize	Peppers	Potatoes	Tomatoes
Maximum water needed (mm/day)	3.14[a]	4.26	9.38	7.94	8.22
Time of year	July[a]	April	June	July	July
Growing season length (days)	214[a]	130	121	129	145
Total dynamic depth (m)	20[a]	300	5	100	55
Operating time (peak hours sun/day)	7.68	6.19	7.23	7.83	7.53
Volumetric flow rate (m^3/s)	0.046	0.077	0.146	0.114	0.123
Power required (kW)	13.9	350.3	11.0	172.0	101.9

[a] From [10].

3. Case studies

3.1. Geographic location selection

Locations selected for case studies have high solar resources, are close to local aquifers and use agricultural irrigation. The selected regions are: Badajoz, Spain; Riyadh, Saudi Arabia; Albuquerque, New Mexico; Tell-Amara, Lebanon; and Wadi-Wala, Jordan. Solar data for these locations are given in the NASA Surface Meteorology and Solar Energy Tables, which is compiled by the Atmospheric Science Data Center at NASA Langley and provides data for any latitude and longitude [26]. The panels are assumed to be flat, horizontal surfaces (no tilt) so the average peak sunshine hours on a horizontal surface at the given locations were used. Crop types and aquifer depths are based on current farming practices in the selected regions [10,27–33]. This information, along with crop water requirements, is presented in Table 2.

With the exception of the data for olive trees in Spain, crop water requirements for the entire growth cycle, from sowing to harvest, were determined using the Food and Agriculture Organization of the United Nations (FAO) CLIMWAT 2.0 database and CROPWAT 8.0 software [14]. CROPWAT uses the Penman–Monteith equations to output a daily evapotranspiration (ET) rate for the crop selected dependent on the climate, altitude, and time of year [34]. This rate changes over the course of the growing season, so the software provides the evapotranspiration rate for the crop for every 10 days of its growing cycle. Fig. 11 shows a sample table for tomatoes grown near Wadi-Wala in Jordan, planted on April 15th.

Table 3 summarizes the parameters that are the same across the representative cases. The system lifetime is assumed to be 25 years, the warranted lifetime of most solar panels [35]. Salvage value of all equipment is assumed to be negligible. The photovoltaic panels and associated electronics are assumed to have an efficiency of 14% [35] and the pump/motor and associated electronics have a subsystem efficiency of 65% [36]. The motor/pump is assumed to run on 220 V.

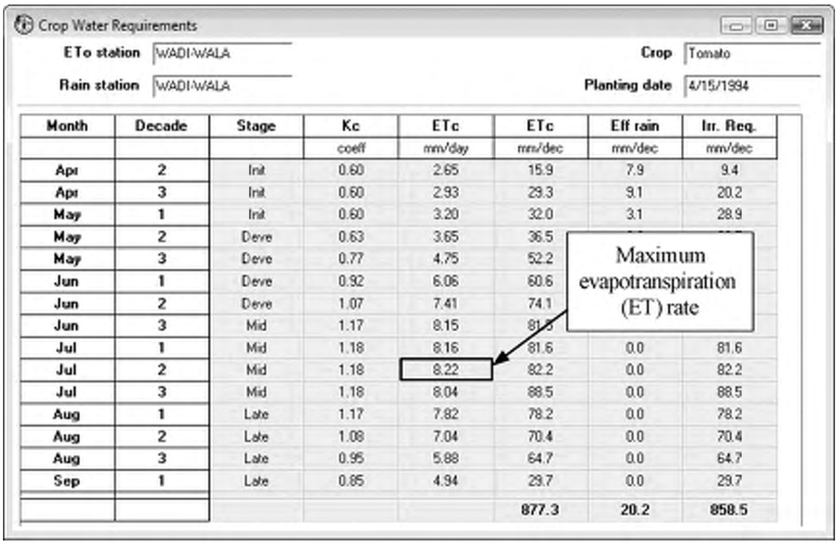
A price of 9.00 USD/W for the PV system is assumed; this is based on analysis of the actual cost of installed PV systems provided by California Solar Statistics [37]. The price for replacement of the electronics associated with the PV systems is 0.72 USD/W [38]. A labor cost of 30.15 USD is assumed [39]. A constant discount rate of 5% is used.

Tables 4–6 show additional parameters used for the economic analysis of the diesel- and grid-powered irrigation systems [19,20,40–44]. Fuel consumption is estimated from the manufacturer's data sheets [20].

As shown in Table 6, electricity prices in Riyadh and Tell-Amara have no associated escalation rates. In Saudi Arabia, the electricity rate has remained constant for the past 10 years. Since the electricity prices are not directly tied to the market and are set by the Electricity and Co-Generation Regulatory Authority, it is unreasonable to assume an escalation rate. No historical data was obtained for electricity prices in Lebanon, so it was not possible to determine an escalation rate. In both cases, electricity prices were assumed constant.

3.2. Technical feasibility

Table 7 shows the required solar panel area for each representative case. The results agree with the analysis shown


Crop Water Requirements

ETo station WADI-WALA Crop Tomato
Rain station WADI-WALA Planting date 4/15/1994

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Apr	2	Init	0.60	2.65	15.9	7.9	9.4
Apr	3	Init	0.60	2.93	29.3	9.1	20.2
May	1	Init	0.60	3.20	32.0	3.1	28.9
May	2	Deve	0.63	3.65	36.5		
May	3	Deve	0.77	4.75	52.2		
Jun	1	Deve	0.92	6.06	60.6		
Jun	2	Deve	1.07	7.41	74.1		
Jun	3	Mid	1.17	8.15	81.5		
Jul	1	Mid	1.18	8.16	81.6	0.0	81.6
Jul	2	Mid	1.18	$\boxed{8.22}$	82.2	0.0	82.2
Jul	3	Mid	1.18	8.04	88.5	0.0	88.5
Aug	1	Late	1.17	7.82	78.2	0.0	78.2
Aug	2	Late	1.08	7.04	70.4	0.0	70.4
Aug	3	Late	0.95	5.88	64.7	0.0	64.7
Sep	1	Late	0.85	4.94	29.7	0.0	29.7
					877.3	20.2	858.5

Fig. 11. Sample of crop water requirements obtained from CROPWAT for tomatoes grown in Wadi-Wala, Jordan. For this case, the tomatoes require the most water in the middle of July.

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Table 3
Additional parameters for all case studies.

Parameter	Value
Peak irradiation I_p (W/m^2)	1000
Solar array efficiency h_{as}	14%
Gravitational constant g (m/s^2)	9.81
Pump efficiency h_p [16]	65%
Discount rate i	5%
System lifetime n (years)	25
Motor/pump voltage	220
Panel cost, including installation (USD/W)	$9.00
Manufacturer solar radiation I_{max} (W/m^2)	1000
Diesel generator load factor F	80%
Diesel generator installation cost (% of capital cost)	10%
Labor cost for maintenance workers (USD/h)	$30.15
Cost of PV electronics replacement (USD/W)	$0.72
Year in which PV electronics are replaced y	15

in Figs. 7–9. As the amount of available solar insolation increases and the amount of water required per day decreases, the amount of land required for the solar array decreases. Furthermore, in all representative cases, the land required for the solar array is less than 1% of the land requiring irrigation. So, provided the land is available, there is no technological barrier to implementation of solar-powered irrigation.

3.3. Economic feasibility

Tables 8–10 show the lifecycle costs of PV, diesel and grid-based systems, respectively.

Capital costs for the PV systems are much higher in all cases; however, lifecycle costs of the PV systems are lower than the diesel and grid systems. In most cases, the PV lifecycle costs are less than half the lifecycle costs of the grid-based systems. The one exception is in Riyadh, where lifecycle costs of the PV and grid systems are about the same, with PV being slightly lower. This is attributed to the low cost of electricity in Saudi Arabia. The lifecycle costs of the grid-based systems are 3–17 times lower than those of the diesel systems, making the PV systems roughly 20 times lower than the diesel systems. These results suggest solar-powered irrigation is economically feasible, even without carbon taxes, renewable energy subsidies and incentives. The lifetime fuel cost is the dominant cost for the diesel and grid-based systems.

Table 4
Sizing parameters for diesel systems, by location.

Parameter	Badajoz	Riyadh	Albuquerque	Tell-Amara	Wadi-Wala
Power required (kW)	13.9	350.3	11.0	172.0	93.3
Required generator power (kW)	17.3	438	14	215	117
Lube oil capacity (L)	1.5	27.2	1.0	40	16.5
Coolant capacity (L)	3.6	57.8	2.5	36	21
Annual operation (h)	2568	1560	1452	1548	1740
Annual oil changes	10	6	6	6	7
Annual oil filter changes	8	5	5	5	6
Annual air filter changes	4	3	2	3	3
Fuel consumption per hour (L/h)	6.2	117.2	4.4	68.8	41.5
Annual amount of fuel required (L)	15,922	182,832	6389	106,502	72,210

Table 5
Sizing parameters for grid-based systems, by location.

Parameter	Badajoz	Riyadh	Albuquerque	Tell-Amara	Wadi-Wala
Power required (kW)	13.9	350.3	11.0	172.0	93.3
Transformer (kVA)	20	400	11	175	112.5
Transformer Weight (lbs)	435	1585	265	845	760

Table 6
Electricity prices and escalation rates by location.

Parameter	Badajoz[a]	Riyadh[b]	Albuquerque[c]	Tell-Amara[d]	Wadi-Wala[e]
Initial electric price (USD/kWh)	0.1200	0.0320	0.0734	0.0766	0.0583
Escalation rate (USD/kWh/year)	0.0103	N/A	0.001132	N/A	0.0007

[a] From [40].
[b] From [42].
[c] From [41].
[d] From [43].
[e] From [44].

Table 7
PV system technical feasibility results.

Parameter	Badajoz	Riyadh	Albuquerque	Tell-Amara	Wadi-Wala
Crop type	Olive trees	Maize	Peppers	Potatoes	Tomatoes
Avg. solar insolation (kWh/day)	7.68	6.19	7.23	7.83	7.53
Power required (kW)	13.9	350.3	11.0	172.0	101.9
Needed panel area (m^2)	99	2502	79	1229	728
Area ratio A_r	0.02%	0.62%	0.02%	0.30%	0.18%

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Table 8
PV system costs.

Parameter	Badajoz	Riyadh	Albuquerque	Tell-Amara	Wadi-Wala
Cost of panels	$124,700	$3,152,500	$99,100	$1,548,400	$916,800
Cost of maintenance labor	$926	$6,501	$880	$3,550	$2,387
Cost of electronics replacement	$997	$25,220	$792	$12,387	$7,334
Annual maintenance cost	$1,923	$32,417	$1,673	$15,937	$9,721
Lifetime maintenance cost	$15,084	$248,789	$13,121	$124,993	$76,246
Total system cost	$139,800	$3,406,700	$112,200	$1,673,400	$993,000

Table 9
Diesel system costs.

Parameter	Badajoz	Riyadh	Albuquerque	Tell-Amara	Wadi-Wala
Cost of diesel engine/generator	$10,000	$52,500	$8,000	$45,000	$25,000
Installation	$1,000	$5,300	$800	$4,500	$2,500
Lifetime maintenance costs	14,800	$19,500	$8,200	$24,400	$16,900
Lifetime operating costs	$7,800	$41,200	$6,300	$35,300	$19,600
Lifetime fuel costs	$4,227,200	$48,541,900	$1,696,200	$28,276,400	$19,171,800
Total lifecycle costs	$4,260,800	$48,660,400	$1,719,500	$28,385,600	$19,235,800

Table 10
Grid-based system costs.

Parameter	Badajoz	Riyadh	Albuquerque	Tell-Amara	Wadi-Wala
Cost of transformer	$8,300	$56,800	$7,600	$25,800	$17,800
Cost of installation	$700	$1,300	$600	$900	$900
Lifetime electricity cost	$1,325,200	$3,428,900	$255,700	$3,994,800	$2,171,200
Total lifecycle cost	$1,334,200	$3,487,400	$263,900	$4,021,500	$2,189,900

Although our lifecycle cost analysis indicates solar-powered irrigation is economically viable, the high capital costs of the PV array mean larger initial cash outlays, which will likely need financing. Depending on the size of the array, this can be difficult. For example, would a farmer in Saudi Arabia be able to finance a $3 million solar array at the assumed discount rate? Lifecycle costs of the PV systems may be lower, but the ability to fund the initial capital costs may provide its own barrier to successful implementation of a solar-powered irrigation system.

4. Conclusions

A method for determining the technical and economic feasibility of PVP irrigation systems, applicable to any geographic location and crop type, is developed and applied to several example cases. Technical feasibility is determined from the maximum power required for irrigation, which is dependent on crop type and geographic location. Economic feasibility is determined by comparing lifecycle costs of PVP irrigation systems to diesel- and grid-based irrigation systems. Carbon taxes and financial incentives for installing alternative energy systems are included in the method, although they are not applied to the examples.

The results of the technical feasibility analysis agree with the results from past studies, and also show that there is no technological barrier to implementation of PVP irrigation. The limiting factor is land availability; as long as there is physical space for the panels, there is no reason why they cannot be used to power an irrigation system. This does not address whether or not it is appropriate to use deep-well sources for crop irrigation in the first place. Pumping from deep-well sources may not be appropriate since they may not be replenished sufficiently each year during the rainy season, or may include non-trivial amounts of heavy metals. Such a discussion is beyond the scope of this work.

The price of diesel fuel has increased significantly since the late 1980s and early 1990s, when many of the previous economic feasibility studies were performed. The results of this study suggest that the price of diesel fuel has increased sufficiently within the last 10 years to make PVP irrigation economically feasible, despite the high capital costs of photovoltaic systems. As the price of the solar panels decreases, the capital costs will decrease, making PVP systems even more economically attractive.

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